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Apparent mass and cross-axis apparent mass of standing subjects during exposure to vertical whole-body vibration

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Abstract

The effects of posture and vibration magnitude on the vertical apparent mass and the fore-and-aft cross-axis apparent mass of the standing human body during exposure to vertical vibration have been investigated. Twelve male subjects were exposed to random vertical vibration over the frequency range 2.0–20 Hz at three vibration magnitudes: 0.125, 0.25 and $0.5\,\mathrm{m\,s^{-2}}$ rms. Subjects stood in five different postures: upright, lordotic, anterior lean, knees bent and knees more bent. The vertical acceleration at the floor and the forces in the vertical and fore-and-aft directions at the floor were used to obtain the apparent mass and the cross-axis apparent mass.

The resonance frequency of the apparent mass was significantly reduced with knees bent and knees more bent postures, but there were only minor effects on the resonance frequency by changing the position of the upper body. Considerable cross-axis apparent mass, up to about 30% of the static mass of subjects, was found. The cross-axis apparent mass was influenced by all postural changes used in the study. In all postures the resonance frequencies of the apparent mass and the cross-axis apparent mass tended to decrease with increasing vibration magnitude. This nonlinear characteristic tended to be less clear in some postures in which subjects increased muscle tension.

1. Introduction

During exposure to vertical vibration, there are significant vertical and fore-and-aft motions in the bodies of standing persons [1]. The fore-and-aft motions of the body that originate from vertical floor vibration may be expected to result in fore-and-aft forces on the floor. Due to symmetry in the human body about the mid-sagittal plane, lateral forces exerted on the floor during vertical vibration may be expected to be relatively small.

Knowledge of dynamic responses at the driving point of the human body is required to predict the dynamic interaction between the human body and supporting structures. The dynamic forces exerted on the floor by the human body in directions other than the direction of excitation may be needed to predict stresses in floor elements. An understanding of the two-dimensional dynamic responses of the body may assist the

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development of models of biodynamic responses to vibration that either advance understanding of the responses of the body or predict forces in practical situations.

Apparent mass frequency response functions have been used to represent the dynamic responses of the body at the driving point (e.g., Refs. [1–9]). The "cross-axis apparent mass" has been used to represent dynamic responses at the driving point in directions other than the direction of excitation. For example, the fore-and-aft dynamic response during exposure to vertical vibration is represented by the fore-and-aft cross-axis apparent mass: the ratio between the fore-and-aft force and the vertical acceleration at the driving point.

The dynamic response of the human body exposed to vibration is influenced by many factors, including body posture and vibration magnitude. With vertical excitation of standing subjects, Coermann [10] found that the resonance frequency of the point mechanical impedance changed from 5.9 to 2 Hz when subjects changed posture from *"standing erect with stiff knees"* to *"bending legs*". Miwa [11] concluded there was no significant difference in mechanical impedance between *"erect"* and *"relaxed"* upper-body postures, both with erect legs. He found, three peaks with similar magnitudes of mechanical impedance at 3, 20 and 60 Hz in a *"knees bending"* posture. Matsumoto and Griffin [1] investigated the effects of leg posture on the apparent mass and found significant reductions in resonance frequencies when bending the knees and also when standing on one leg.

The fore-and-aft dynamic forces occurring during the vertical vibration of standing persons have not been previously investigated. However, a few studies have investigated the fore-and-aft forces with seated subjects exposed to vertical excitation [2,3]. Nawayseh and Griffin [3] found that the fore-and-aft cross-axis apparent mass at the seat varies with posture. Even slight changes in the postures of seated or standing subjects might be expected to modify the fore-and-aft driving point dynamic response due to changes in the position of the centre of gravity of the body in the anteroposterior direction.

In previous studies (e.g., Refs. [1–8,12]), it has been consistently found that the dynamic response of the body exposed to vertical vibration is nonlinear: the resonance frequency of the apparent mass decreases with increasing vibration magnitude. This "softening" effect has been found in the human body in both seated and standing positions. A decrease in the resonance frequency of the apparent mass with increasing vibration magnitude has also been observed with seated subjects exposed to horizontal vibration. Fairley and Griffin [9] found nonlinear characteristics in a resonance between 1.5 and 3 Hz in the fore-and-aft apparent masses of seated subjects. A similar nonlinearity has been observed in the transmission of vertical vibration from the excitation point to various locations on the body in the vertical and the fore-and-aft directions with both seated subjects [5,6] and standing subjects [1]. Nonlinear characteristics in the vertical apparent mass, horizontal apparent mass and transmissibilities (i.e., ratio between two motions measured at different locations) to various locations on the body are consistent with the reported nonlinear characteristics in fore-and-aft cross-axis apparent mass during vertical excitation [3,4].

The mechanism responsible for the nonlinear dynamic responses has not been established, although some possible causes have been suggested. Mansfield and Griffin [6] hypothesized that the nonlinearity in the dynamic response of seated subjects may be caused by a complex combination of factors, including the dynamic characteristics of tissue beneath the ischial tuberosities, the bending or buckling response of the spine and the active responses of the muscles. Mathematical models by Kitazaki and Griffin [13] and Matsumoto and Griffin [14] suggest that bending and buckling of the spine make minor contributions to the principal resonance of the apparent mass. In an experimental study, a similar softening characteristic has been observed in the seated position with a bent spine and an upright posture [8], implying that bending and buckling of the spine make only a minor contribution to the nonlinearity in the apparent mass.

As standing and seated subjects show similar nonlinear dynamic responses to vertical vibration, there may be the same or similar properties of the human body responsible for nonlinearity in both positions. A study of the effect of muscle tension on the nonlinearity in the apparent masses of seated subjects found that changes in resonance frequencies decreased in sitting conditions with tensed abdominal and buttock muscles, compared with an upright sitting posture with normal muscle tension [2]. This suggests that involuntary changes in muscle tension during exposure to vibration might be partly responsible for the nonlinear dynamic response of the human body. In a standing posture, reductions in the nonlinearity of the dynamic response might therefore be expected with increased muscle tension in either the upper body or the lower limb, assuming that increased muscle tension reduces involuntary changes in muscle activity during vibration.

The objective of this study was to investigate the vertical apparent masses and the cross-axis apparent masses of standing subjects exposed to vertical vibration. There were three specific aspects investigated: (i) the characteristics of the fore-and-aft force at the floor induced by standing subjects exposed to vertical vibration, (ii) the effect of postural changes on the forces at the floor in the vertical and fore-and-aft directions, and (iii) the effect of muscle tension on the nonlinearity observed in the response of the body. It was hypothesised that there would be a considerable fore-and-aft cross-axis apparent mass with resonances associated with the resonances in the vertical apparent mass. It was therefore expected that the vertical apparent mass and the cross-axis apparent mass would be similarly affected by changes in posture and vibration magnitude. It was further hypothesised that the nonlinearity in the dynamic responses of the standing subjects would decrease with increased muscle tension.

2. Method

This experiment was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research (ISVR) at the University of Southampton prior to the commencement of the experiment in a laboratory at the ISVR.

2.1. Subjects

Twelve male subjects with a median age of 28 years (range 22–48 years), height 1.79 m (range 1.65–1.96 m), and weight 77.45 kg (range 65.60–101.95 kg) participated in the experiment. The subjects were students and staff of the ISVR. Prior to the commencement of the experiment, subjects gave their written consent to participate in accord with the policy of the ISVR on research involving human subjects.

2.2. Apparatus

An electro-dynamic vibrator, Derritron VP180 (Hastings, England), was used to generate vertical vibration. A tri-axial force platform, Kistler 9281 B (Kistler AG, Switzerland) was used to measure forces in the vertical and fore-and-aft directions. The force platform ($600 \times 400 \times 20$ mm), consisting of four tri-axial quartz piezoelectric force transducers, was rigidly fixed to the vibrator. Vertical acceleration of the top plate of the force platform was measured using a piezoresistive uni-axial accelerometer, Entran EGCSY-240D*-10. An *HVLab* data acquisition and analysis system (version 3.81) was used to produce motions and acquire signals from the transducers. Signals from the accelerometer and the force transducers were digitized at 128 samples per second after low pass filtering at 35 Hz.

2.3. Experimental protocol

Subjects were exposed to random vertical vibration with an approximately flat constant-bandwidth acceleration power spectrum over the frequency range 2–20 Hz at three different vibration magnitudes: 0.125, 0.25 and 0.5 $\mathrm{m\,s^{-2}}$ rms. The duration of each exposure was 60 s. The same acceleration waveform at three different magnitudes was used for all excitations.

During the experiment, subjects were instructed to stand with three different upper-body postures and two different lower limb postures. The five postures used in the experiment are described in Table 1. The lordotic and anterior lean postures were used to investigate effects of upper-body posture. An anterior lean posture involved increased tension mainly in the back extensor muscles, while a lordotic posture involved increased tension mainly in the abdominal muscles. Additionally, both postures involved increased muscle tension in the legs. The knees bent posture involved keeping the knees vertically above the toes. In this posture, the muscle tension of the lower limb was probably increased. A further increase of lower limb muscle tension was achieved by increased bending of the knees. In all postures, subjects stood with bare feet separated by 30 cm at their big toes and by 25 cm at their heels. Except in the knees bent posture and the knees more bent posture, subjects stood with their legs straight and locked. In the two postures with bent legs, the angle between the lower legs and the upper legs was specified by the experimenter.

Table 1
Description of postures

Posture	Description
Upright	Comfortable upright posture with normal muscle tension
Lordotic	Lean upper body slightly backward so as to keep lumbar spine at maximum bend
Anterior lean	Lean upper body slightly forward so as to align shoulders vertically above the toes
Knees bent	Knees bent with an angle of 120° between lower legs and upper legs
Knees more bent	Knees bent with an angle of 110° between lower legs and upper legs

For safety purpose, subjects were asked to hold lightly with both hands to a rigid frame fixed in front of them. Subjects were further instructed to avoid any voluntary movements of the body, keep their eyes open, look straight ahead and maintain the same standing position during each exposure.

The order of presenting the three vibration magnitudes and the five postures was randomized for each subject.

2.4. Analysis

From the measured vertical acceleration and dual-axis force signals, the vertical apparent mass and the fore-and-aft cross-axis apparent mass were calculated. Both the vertical apparent mass and the fore-and-aft cross-axis apparent mass were calculated using the cross spectral density method:

$$M(\omega) = \frac{S_{\mathrm{af}}(\omega)}{S_{\mathrm{aa}}(\omega)}, \tag{1}$$

where $S_{\mathrm{af}}(\omega)$ is the cross spectral density between the force and the vertical floor acceleration and $S_{\mathrm{aa}}(\omega)$ is the power spectral density of the vertical floor acceleration.

The measured force in the vertical direction included the effect of the mass of the parts of the force platform located above the force transducers. This effect must be excluded to obtain the vertical apparent mass of the subject. The measurement of the vertical apparent mass without a subject showed that the real part of the apparent mass was nominally constant and the imaginary part was nominally zero over the frequency range of interest. This indicates that the parts above the transducers behaved as a rigid mass in the frequency range used in the experiment. Therefore, the real part of the vertical apparent mass obtained without a subject, which was identical to the static mass of the parts of the force platform above the force transducers, was subtracted from the real part of the vertical apparent mass transfer function obtained with a subject so as to eliminate the effect of the mass of the parts of the force platform located above the force transducers. The measurement of the fore-and-aft cross-axis apparent mass without a subject showed that the real part and the imaginary part were nominally zero over the frequency range of interest. This indicates that there was no movement of the force platform in the fore-and-aft direction. Therefore, mass cancellation was not required for the calculation of the fore-and-aft cross-axis apparent mass.

The apparent masses obtained for each subject from the cross spectral density method were normalized by dividing by the static weight of each subject, so as to minimize the inter-subject variability caused by the different mass of each subject.

3. Results

3.1. Vertical apparent mass

Fig. 1 shows the inter-subject variability in the normalized vertical apparent masses in all postures at a vibration magnitude of $0.5\,\mathrm{m\,s^{-2}}$ rms. In each posture, subjects showed similar general characteristics in the vertical apparent mass, although with the three different upper-body postures, a second resonance in the frequency range from 8 to 13 Hz was clearer for some than others. In the ‘‘knees bent’’ posture and the ‘‘knees

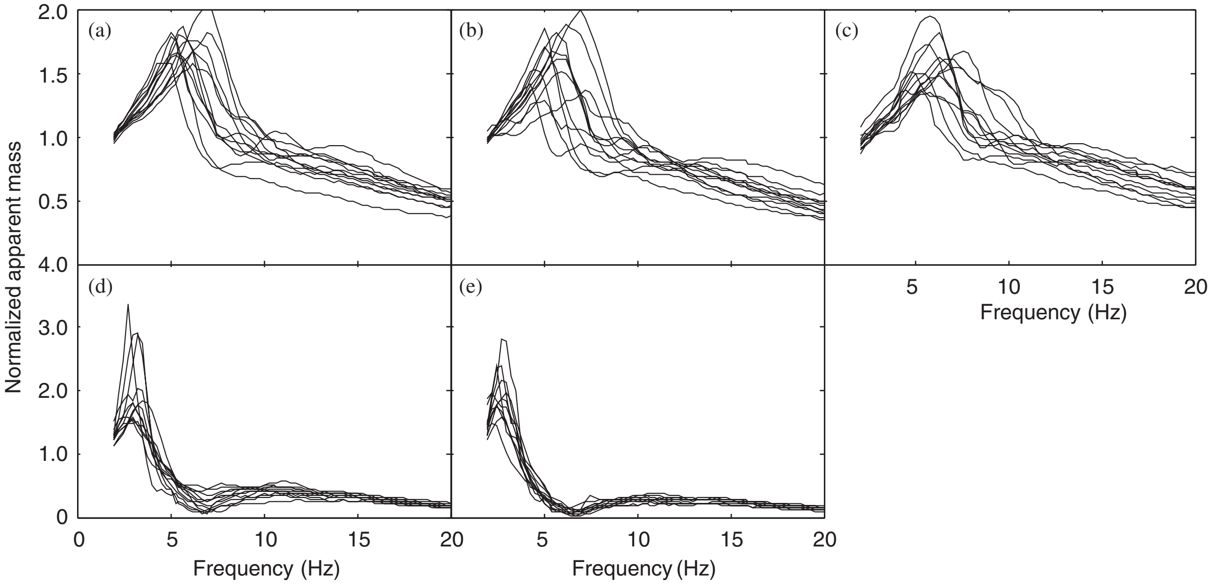

Fig. 1. Normalized vertical apparent masses of 12 subjects at $0.5\,\mathrm{m\,s^{-2}}$ rms in five postures. (a) upright, (b) lordotic, (c) anterior lean, (d) knees bent and (e) knees more bent.

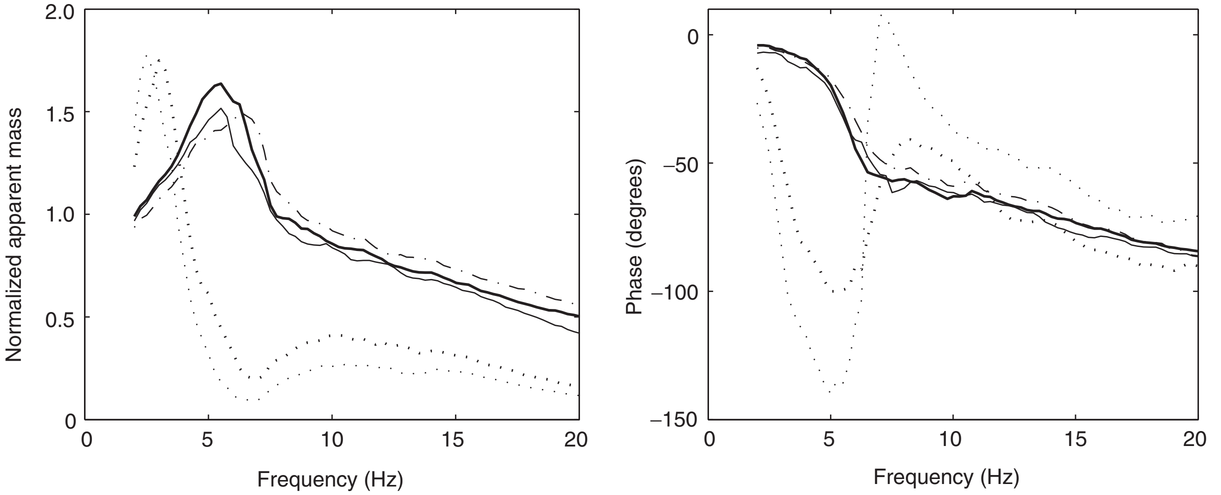

Fig. 2. Median normalized vertical apparent mass and phase of twelve subjects at $0.5\,\mathrm{ms^{-2}}$ rms in five postures. ——— upright, ——— lordotic, —·—·· anterior lean, ··········· knees bent, - - - - - knees more bent.

more bent” posture, most subjects showed a broad minor peak around 12 Hz in addition to a more distinct peak at lower frequencies.

3.1.1. *Effect of posture on vertical apparent mass*

The median normalized vertical apparent masses and phases of the 12 subjects calculated for all postures at a vibration magnitude of $0.5\,\mathrm{m\,s^{-2}}$ rms are shown in Fig. 2. In the upright posture, the median resonance frequency in the normalized apparent mass is at 5.63 Hz. The resonance frequency of the apparent mass was less affected by postural changes with locked knees (upright, lordotic or anterior lean postures) than by postural changes in the lower limbs (“knees bent” or “knees more bent” postures). In the “knees bent” posture, the apparent mass showed a median resonance frequency of 3.13 Hz, together with a minor broad peak around 12 Hz. With decreasing angle between the lower legs and the upper legs (i.e. the "knees more bent" posture), the main resonance decreased to 2.63 Hz.

For all postures, the median resonance frequency of the normalized apparent mass and the median normalized apparent mass at the resonance frequency of individual data are listed in Table 2. The resonance frequency of the apparent mass was affected by the lower limb postures but there was a minor effect of upper-body posture on the resonance of the apparent mass. At most vibration magnitudes, the lowest median apparent mass at the resonance frequency was in the anterior lean posture.

The differences in the resonance frequencies of the apparent mass, and differences in the apparent masses at the resonance frequency, between the upright posture and the other four postures were investigated statistically (Table 3). There was no statistically significant difference in the resonance frequency at any vibration magnitude between the upright posture and the lordotic posture. The small difference in the resonance frequency between the upright posture and the anterior lean posture was not statistically significant at any vibration magnitude, except at $0.5\,\mathrm{m\,s^{-2}}$ rms. At all vibration magnitudes, there were significant differences in the resonance frequencies between the upright posture and the "knees bent" posture and between the upright posture and the "knees more bent" posture ($p<0.01$, Wilcoxon). The resonance frequencies were also significantly different between the "knees bent" posture and the "knees more bent" posture at each vibration magnitude ($p<0.01$, Wilcoxon). There was a statistically significant difference in the apparent mass at the resonance frequency between the upright posture and the lordotic posture at all vibration magnitudes, except $0.5\,\mathrm{m\,s^{-2}}$ rms. The differences in the apparent mass at the resonance were statistically significant between the upright posture and the anterior lean posture at vibration magnitudes of 0.125 and $0.5\,\mathrm{m\,s^{-2}}$ rms. Differences in the apparent mass at resonance were statistically significant between the upright posture and the "knees bent" posture at a vibration magnitude of $0.125\,\mathrm{m\,s^{-2}}$ rms only. There was no statistically significant difference in the apparent mass at resonance between the upright posture and the "knees more bent" posture.

Table 2
Median resonance frequencies of the normalized apparent masses and the normalized apparent masses at resonance for twelve subjects

Posture	Resonance frequency (Hz)			Normalized apparent mass		
	0.125	0.25	0.5	0.125	0.25	0.5
Upright	6.39	6.01	5.63	1.89	1.83	1.77
Lordotic	6.26	5.76	5.63	1.66	1.58	1.64
Anterior lean	7.01	6.51	6.01	1.61	1.64	1.58
Knees bent	3.51	3.26	3.13	1.70	1.74	1.82
Knees more bent	3.01	2.63	2.63	1.90	1.71	1.92

Table 3
Statistical significances of effects of posture on the resonance frequency of the apparent mass and the apparent mass at resonance: comparison with upright posture

Posture	Resonance frequency			Apparent mass		
	0.125	0.25	0.5	0.125	0.25	0.5
Lordotic	0.356	0.147	0.399	0.002**	0.008**	0.099
Anterior lean	0.417	0.248	0.024*	0.019*	0.060	0.045*
Knees bent	0.002**	0.002**	0.002**	0.008**	0.814	0.209
Knees more bent	0.002**	0.002**	0.002**	0.530	0.814	0.136

Wilcoxon matched-pairs signed rank test. *$p<0.05$, **$p<0.01$.

3.1.2. Effect of vibration magnitude on vertical apparent mass

The apparent mass resonance frequency tended to decrease with increasing vibration magnitude for every subject in all postures. The median normalized apparent masses and phases calculated for all postures at the three vibration magnitudes are shown in Fig. 3. A nonlinearity in the apparent mass with vibration magnitude is present in all postures, although the degree of the nonlinearity differs between postures (Table 2). In the upright posture, the resonance frequency decreased from 6.39 to 5.63 Hz as vibration magnitude increased from 0.125 to 0.5 m s^{-2} rms. The absolute change in the resonance frequency tended to be less in the other postures, except the anterior lean posture (Table 2). The percentage change in the resonance frequency with increasing vibration magnitude from 0.125 to 0.5 m s^{-2} rms was slightly less in the lordotic posture (10.1%)

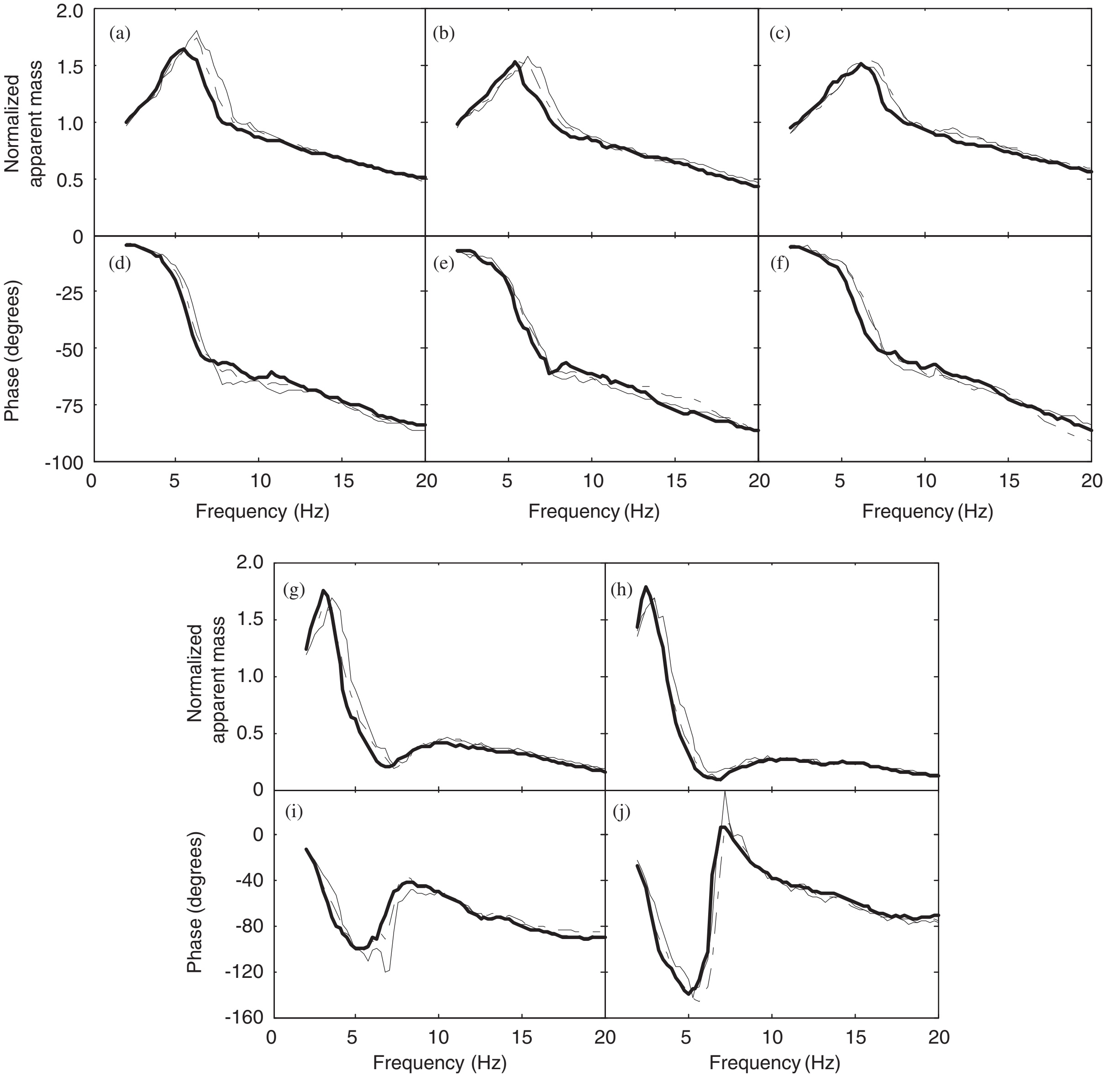

Fig. 3. Median normalized vertical apparent masses and phases of 12 subjects at three vibration magnitudes with five postures. (a and d) upright, (b and e) lordotic, (c and f) anterior lean, (g and i) knees bent, (h and j) knees more bent. — 0.125 m s^{-2} rms, -·- 0.25 m s^{-2} rms, ▬ 0.5 m s^{-2} rms.

Table 4
Statistical significances of effects of vibration magnitude on the resonance frequency of the apparent mass and the apparent mass at resonance

Posture	Vibration magnitude ($\mathrm{m\,s^{-2}}$ rms)	Resonance frequency		Apparent mass	
		0.25	0.5	0.25	0.5
Upright	0.125	0.005**	0.002**	0.015*	0.010**
	0.25	—	0.017*	—	0.388
Lordotic	0.125	0.050*	0.002**	0.209	0.583
	0.25	—	0.326	—	0.695
Anterior lean	0.125	0.031*	0.007**	0.480	0.147
	0.25	—	0.011*	—	0.875
Knees bent	0.125	0.031*	0.007**	0.071	0.099
	0.25	—	0.088	—	0.480
Knees more bent	0.125	0.011*	0.018*	0.209	0.937
	0.25	—	0.308	—	0.480

Wilcoxon matched-pairs signed rank test. $^{*}p<0.05$, $^{**}p<0.01$.

and in the "knees bent" posture (10.8%) than in the upright posture (11.9%) but greater in the anterior lean posture (14.3%) and in the "knees more bent" posture (12.6%).

The statistical significance of the changes in the resonance frequencies of the apparent mass and the apparent mass at resonance with a change in vibration magnitude in each posture are summarized in Table 4. There was a statistically significant reduction in the resonance frequency with increasing vibration magnitude from 0.125 to 0.25 $\mathrm{m\,s^{-2}}$ rms and from 0.125 to 0.5 $\mathrm{m\,s^{-2}}$ rms in all postures ($p<0.05$, Wilcoxon). With an increase in vibration magnitude from 0.25 to 0.5 $\mathrm{m\,s^{-2}}$ rms, a statistically significant reduction in the resonance frequency was found in the upright posture and in the anterior lean posture only.

To investigate the effect of posture on the changes in the resonance frequency caused by changing vibration magnitude, the size of statistically significant differences in the resonance frequency, both the absolute values and the values in percentages, were analysed statistically. The size of absolute differences in the resonance frequency between 0.125 and 0.5 $\mathrm{m\,s^{-2}}$ rms and between 0.25 and 0.5 $\mathrm{m\,s^{-2}}$ rms was significantly smaller in the "knees more bent" posture than that in the upright posture ($p<0.05$, Wilcoxon). The sizes of differences in the resonance frequencies at different vibration magnitudes for the anterior lean posture, for the lordotic posture and for the "knees bent" posture were not significantly different from those for the upright posture ($p>0.05$, Wilcoxon). The size of differences in the percentage change in the resonance frequency between the vibration magnitudes for the lordotic posture, the anterior lean posture, the "knees bent" posture and the "knees more bent" posture were not significantly changed from those for the upright posture ($p>0.05$, Wilcoxon).

In the upright posture, the apparent mass at the resonance frequency tended to decrease with increasing vibration magnitude: the reduction in the apparent mass at the resonance frequency was statistically significant when the vibration magnitude increased from 0.125 to 0.25 and 0.5 $\mathrm{m\,s^{-2}}$ rms (Table 4). Changes in the apparent mass at the resonance frequency were not statistically significant in any of the other four postures ($p>0.05$, Wilcoxon).

3.2. Cross-axis apparent mass

The fore-and-aft cross-axis apparent masses of all subjects at a vibration magnitude of 0.5 $\mathrm{m\,s^{-2}}$ rms are shown for all postures in Fig. 4. There was an appreciable cross-axis apparent mass for most individuals in all postures, except the anterior lean posture. Most subjects showed two clear peaks in the fore-and-aft cross-axis apparent mass, although some subjects showed three peaks in all postures. Variability between subjects is large for the three upper-body postures. In the "knees more bent" posture, a similar general characteristics of the cross-axis apparent mass can be seen in most individual data.

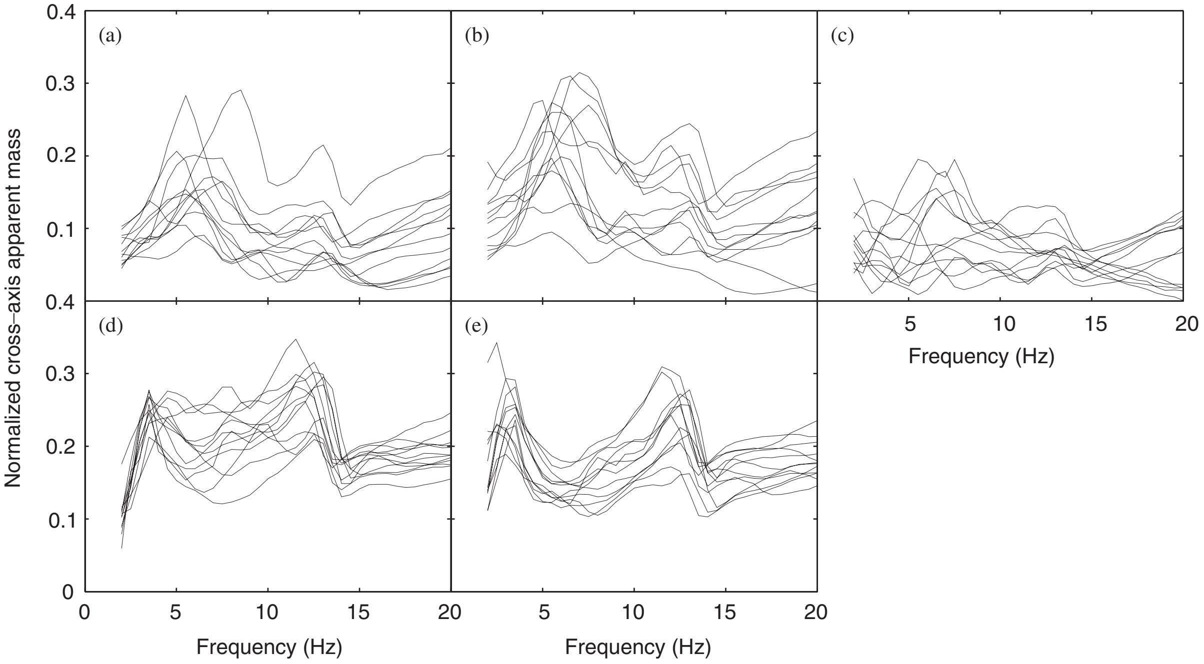

Fig. 4. Normalized fore-and-aft cross-axis apparent masses of 12 subjects at $0.5\,\mathrm{m\,s^{-2}}$ rms in five postures. (a) upright, (b) lordotic, (c) anterior lean, (d) knees bent and (e) knees more bent.

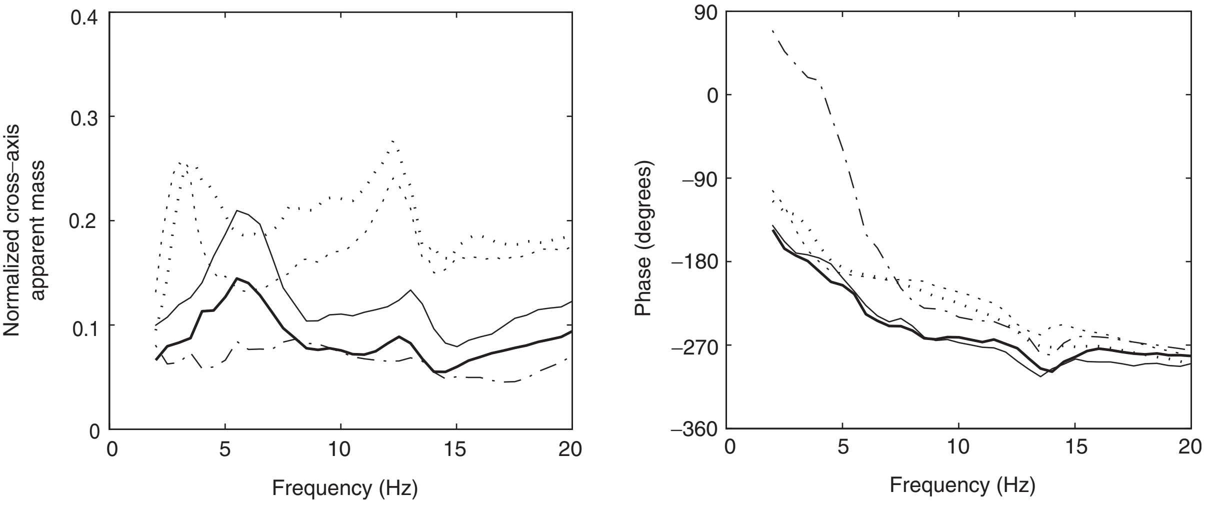

Fig. 5. Median normalized fore-and-aft cross-axis apparent mass and phase of twelve subjects at $0.5\,\mathrm{ms^{-2}}$ rms in five postures. ━━━ upright, ——— lordotic, —·—·· anterior lean, ·········· knees bent, ‒ ‒ ‒ ‒ knees more bent.

3.2.1. Effect of posture on the cross-axis apparent mass

The median normalized fore-and-aft cross-axis apparent masses and phases of the 12 subjects in all postures at a vibration magnitude of $0.5\,\mathrm{m\,s^{-2}}$ rms are shown in Fig. 5. The fore-and-aft response of the human body was clearly affected by body posture. In the upright posture, the median cross-axis apparent mass shows a main resonance around 6 Hz, together with a minor resonance around 12 Hz. The two clear peaks in the median cross-axis apparent mass in the upright posture are more pronounced in the lordotic posture. In the anterior lean posture, there is no peak in the median cross-axis apparent mass, although six subjects show

Table 5
Median first resonance frequencies of the normalized cross-axis apparent mass and the normalized cross-axis apparent masses at the first resonance for twelve subjects

Posture	Resonance frequency (Hz)			Normalized cross-axis apparent mass		
	0.125	0.25	0.5	0.125	0.25	0.5
Upright	6.51	6.26	5.88	0.21	0.23	0.17
Lordotic	6.26	6.26	5.63	0.29	0.24	0.27
Anterior lean	—	—	—	—	—	—
Knees bent	4.26	4.26	3.76	0.29	0.28	0.27
Knees more bent	3.01	3.01	3.01	0.26	0.27	0.27

Table 6
Statistical significances of the effects of posture on the first resonance frequency of the cross-axis apparent mass and the cross-axis apparent mass at the first resonance: comparison with upright posture

Posture	Resonance frequency			Cross-axis apparent mass		
	0.125	0.25	0.5	0.125	0.25	0.5
Lordotic	0.350	0.513	0.185	0.099	0.307	0.021*
Anterior lean	—	—	—	—	—	—
Knees bent	0.002**	0.002**	0.004**	0.023*	0.010**	0.005**
Knees more bent	0.002**	0.002**	0.002**	0.041*	0.003**	0.005**

Wilcoxon matched-pairs signed rank test. *$p<0.05$, **$p<0.01$.

some peaks in the cross-axis apparent mass: the peaks appearing at different frequencies resulted in the effect of the peaks being spread over a range of frequencies during the calculation of median responses. The lowest resonance frequency in the median cross-axis apparent mass was around 4 Hz in the "knees bent" posture and around 3 Hz in the "knees more bent" posture. In these postures, a second resonance was apparent around 12 Hz.

Table 5 shows the median of the lowest resonance frequency in the cross-axis apparent mass and the median cross-axis apparent mass at this resonance in the individual data. Median values for the anterior lean posture were not determined, as six subjects did not show a clear peak in the cross-axis apparent mass. The effects of posture on the first resonance frequency of the cross-axis apparent mass and the cross-axis apparent mass at the first resonance frequency were compared statistically between the upright posture and the other postures (Table 6). At no vibration magnitude was there a significant difference in the resonance frequency of the cross-axis apparent mass between the upright posture and the lordotic posture. However, there was a significant difference in the cross-axis apparent mass at this resonance between the upright posture and the lordotic posture at a vibration magnitude of $0.5\,\mathrm{m\,s^{-2}}$ rms. At each vibration magnitude, there was a significant difference in the first resonance frequency of the cross-axis apparent mass between the "knees bent" posture and the upright posture and between the "knees more bent" posture and the upright posture. The cross-axis apparent mass at this resonance also differed significantly between these postures at each vibration magnitude (Table 6 and Fig. 5).

3.2.2. Effect of vibration magnitude on the cross-axis apparent mass

The median normalized fore-and-aft cross-axis apparent masses and the median phases of the fore-and-aft cross-axis apparent masses for the 12 subjects at the three vibration magnitudes in all five postures are shown in Fig. 6. The first resonance frequency of the cross-axis apparent mass tended to decrease with

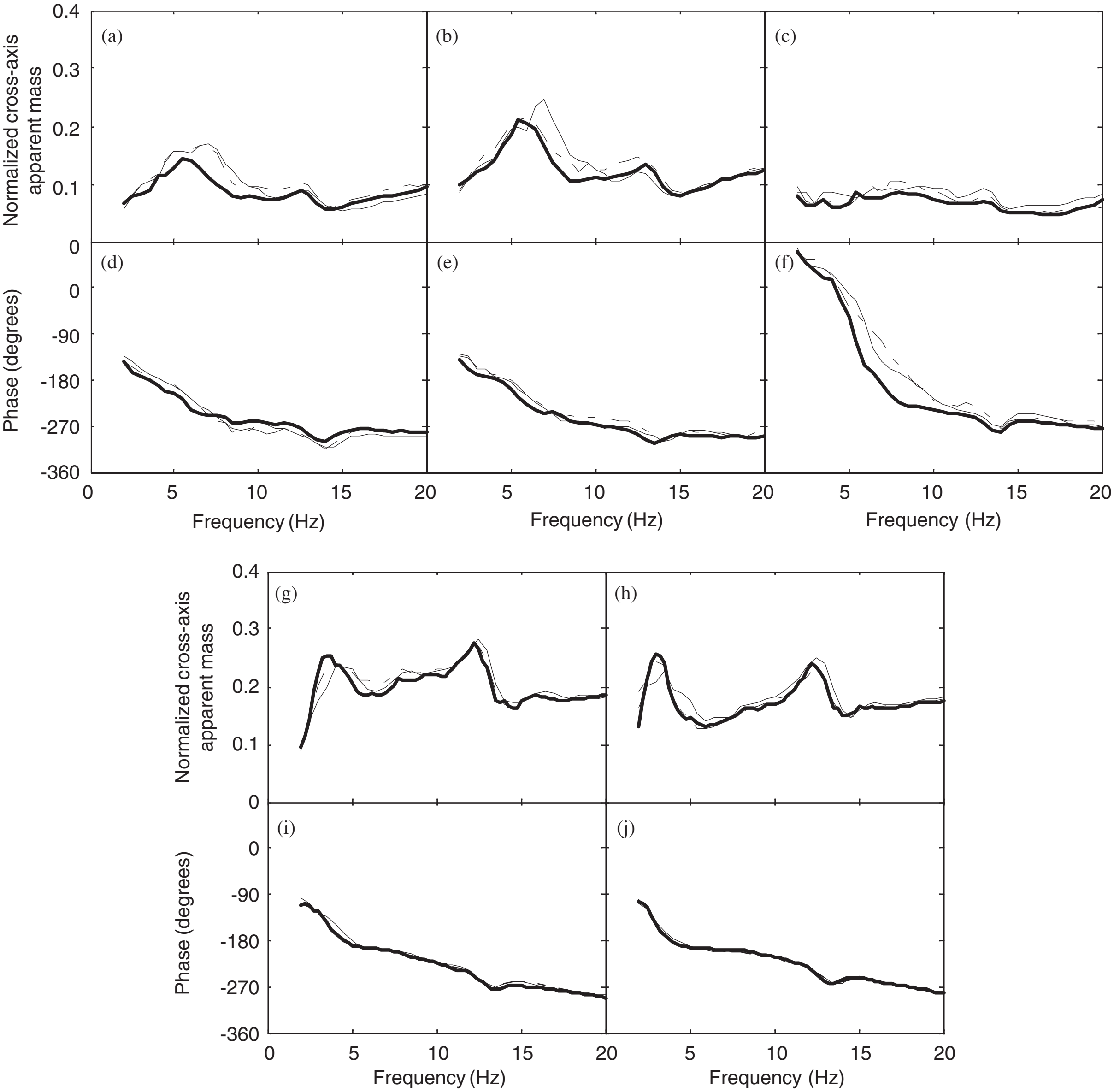

Fig. 6. Median normalized fore-and-aft cross-axis apparent masses and phases of 12 subjects at three vibration magnitudes with five postures. (a and d) upright, (b and e) lordotic, (c and f) anterior lean, (g and i) knees bent, (h and j) knees more bent. — 0.125 m s^{-2} rms, -·- 0.25 m s^{-2} rms, ▬ 0.5 m s^{-2} rms.

increasing vibration magnitude, although the reductions in the resonance frequency with increasing vibration magnitudes were not as clearly statistically significant as the changes in the vertical apparent mass (Table 7).

3.3. Correlation between the apparent mass and the cross-axis apparent mass

Correlations between the resonance frequencies of the vertical apparent mass and the cross-axis apparent mass were investigated using the Kendall rank-order correlation coefficient (Table 8). The correlation between resonance frequencies was not investigated in the anterior lean posture because there were insufficiently clear

Table 7
Statistical significances of the effects of vibration magnitude on the first resonance frequency of the apparent mass and the apparent mass at the first resonance

Posture	Vibration magnitude ($m\,s^{-2}$ rms)	Resonance frequency		Cross-axis apparent mass	
		0.25	0.5	0.25	0.5
Upright	0.125	0.017*	0.151	0.937	0.091
	0.25	—	0.444	—	0.010**
Lordotic	0.125	0.605	0.069	0.814	0.117
	0.25	—	0.061	—	0.638
Anterior lean	0.125	—	—	—	—
	0.25		—		—
Knees bent	0.125	0.540	0.202	0.906	0.099
	0.25	—	0.454	—	0.130
Knees more bent	0.125	0.256	0.136	0.666	0.583
	0.25	—	0.518	—	0.248

Wilcoxon matched-pairs signed rank test. $^{*}p<0.05$, $^{**}p<0.01$.

Table 8
Statistical significance of correlations between the resonance frequencies of apparent mass and the cross-axis apparent mass

Posture	Vibration magnitude ($m\,s^{-2}$ rms)		
	0.125	0.25	0.5
Upright	0.837***	0.902***	0.492*
Lordotic	0.607**	−0.017	0.640**
Anterior lean	—	—	—
Knees bent	0.541*	0.581*	0.509*
Knees more bent	0.627*	0.597*	0.531*

Kendall rank-order correlation coefficient. $^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$.

Table 9
Statistical significances of differences between the resonance frequencies of apparent mass and the cross-axis apparent mass

Posture	Vibration magnitude ($m\,s^{-2}$ rms)		
	0.125	0.25	0.5
Upright	0.671	0.154	0.258
Lordotic	0.362	0.559	0.344
Anterior lean	—	—	—
Knees bent	0.015*	0.003**	0.002**
Knees more bent	0.058	0.011*	0.005**

Wilcoxon matched-pairs signed rank test. $^{*}p<0.05$, $^{**}p<0.01$.

resonances in the cross-axis apparent mass in half of the subjects. There were statistically significant correlations between the first resonance frequencies of the apparent mass and the cross-axis apparent mass in all postures at all vibration magnitudes, except in the lordotic posture at a vibration magnitude of $0.25\,m\,s^{-2}$ rms. The first resonance frequencies in the vertical apparent mass and the first resonance frequencies in the cross-axis apparent mass did not differ significantly, except for all three vibration magnitudes in the "knees bent" posture and for two highest vibration magnitudes in the "knees more bent" posture ($p>0.05$, Wilcoxon) (Table 9).

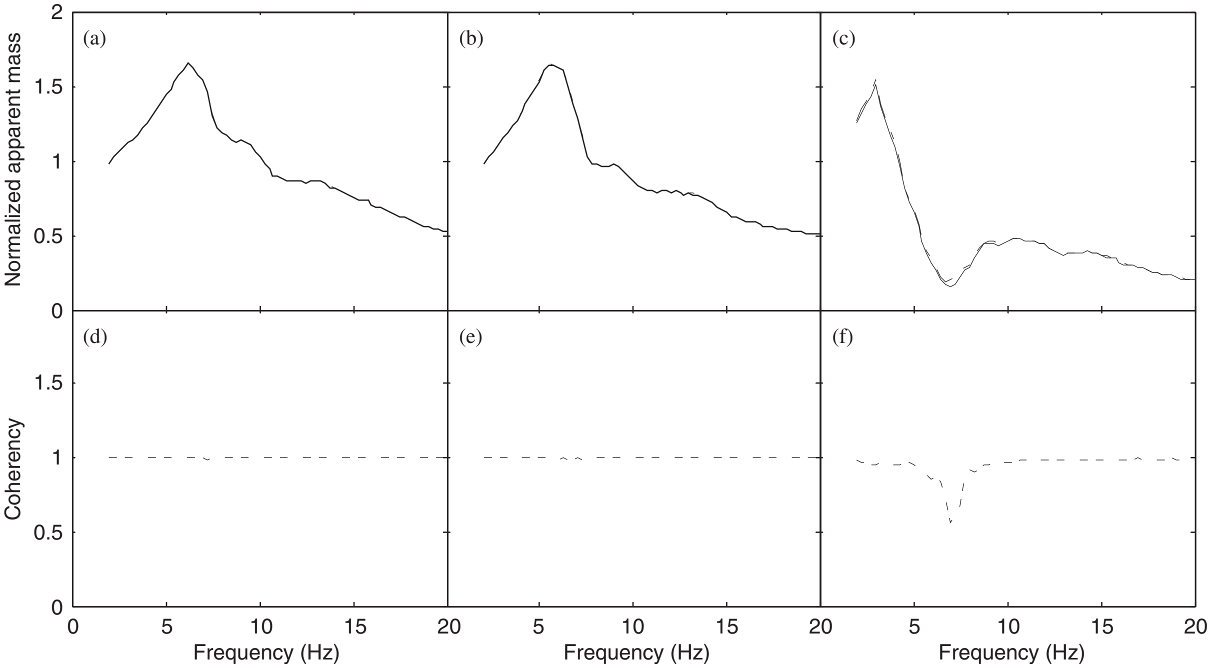

Fig. 7. Normalized apparent mass and coherence of one subject at 0.5 m s^{-2} rms with three postures. (a and d) upright, (b and e) lordotic, (c and f) knees bent. — CSD method, -·- PSD method, - - - - - coherency.

4. Discussion

4.1. Validity of using linear analysis techniques

It may not seem that the cross spectral density method, which is a linear technique, is appropriate to investigate the nonlinear dynamic responses of humans, although the method is preferred because it gives the phase between the force and the acceleration. The apparent masses obtained from the "cross spectral density method" used above and the "power spectral density method", defined as the square root of the ratio of the power spectral densities of force and acceleration (which includes any nonlinearity involved in the system) were therefore compared. Fig. 7 compares the vertical apparent mass of one subject measured at 0.5 m s^{-2} rms for the upright posture, for the lordotic posture (one of the different upper-body postures) and for the "knees bent" posture (one of the different lower-limb postures) obtained using the "cross spectral density method" and the "power spectral density method". For this comparison, the apparent mass was obtained after subtracting the vertical force due to the mass of parts of the force platform above the transducers from the measured vertical force in the time domain, on the assumption that the parts above the transducers were rigid in the frequency range of interest. The cross-axis apparent masses of the same subject measured at 0.5 m s^{-2} rms for the three different postures (upright, lordotic and "knees bent") obtained from the two methods are compared in Fig. 8. Figs. 7 and 8 also show the coherencies of the corresponding apparent masses and the cross-axis apparent masses. The coherency of the apparent mass was calculated after subtracting in the time-domain the vertical force due to the mass of those parts of the force platform above transducers from the measured vertical force.

It was found that the two analysis methods provided almost identical vertical apparent masses. For the fore-and-aft cross-axis apparent mass, the two methods provided similar values: the maximum difference was less than 3.1%. This may suggest that the human body behaves as a linear system at one vibration magnitude, although modifying its response for another vibration magnitude. The use of linear techniques (i.e., the cross spectral density method) may often be sufficient when analysing the response at one vibration magnitude.

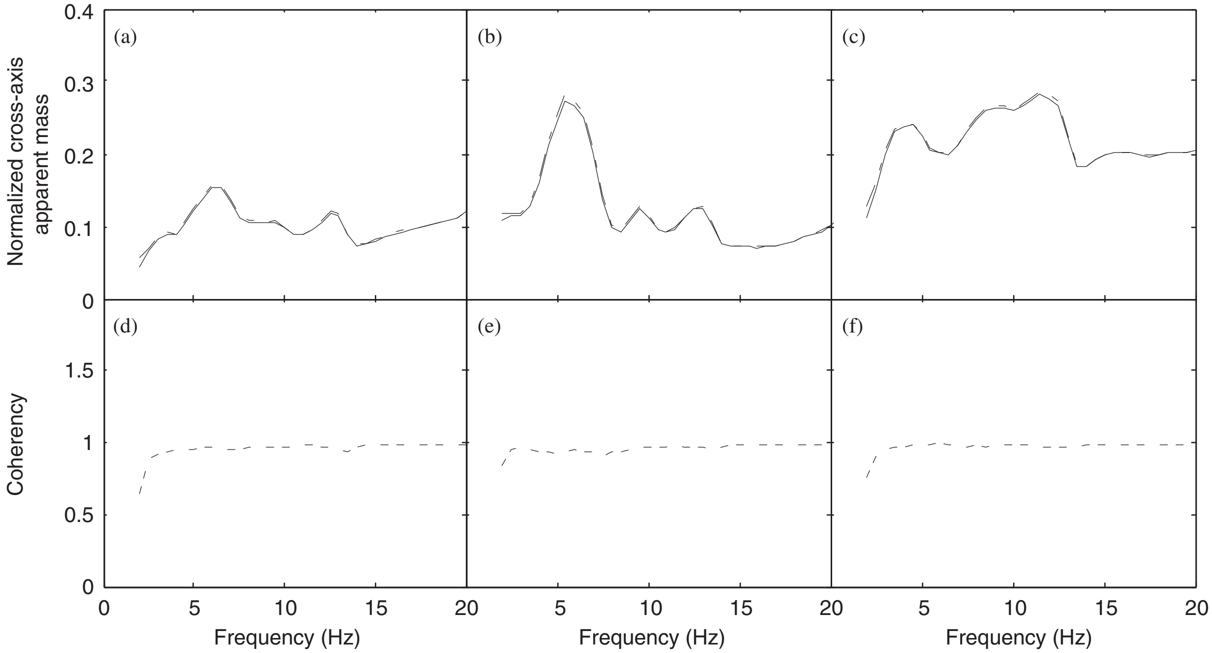

Fig. 8. Normalized cross-axis apparent mass and coherence of one subject at 0.5 m s^{-2} rms with three postures. (a and d) upright, (b and e) lordotic, (c and f) knees bent. ▬ CSD method, -·- PSD method, - - - - - coherency.

4.2. Effect of posture on vertical apparent mass

The principal resonance frequency of the apparent mass observed around 5 Hz in the upright posture was not significantly changed when bending the spine in the lordotic and anterior lean postures, except between the upright posture and the anterior lean posture at 0.5 m s^{-2} rms (Fig. 2 and Table 3). Mansfield and Griffin [8] observed similar results for seated subjects with no backrest, between a comfortable upright posture and an upper-body lean posture: changes of the resonance frequency with posture were not generally statistically significant. It has been reported that there may be only minor contributions of bending motions of the spine to the principal resonance of the apparent mass of seated subjects [14]. The results shown in Fig. 2 and Table 3, together with the findings for seated subjects described above, imply that the contribution of bending motions of the spine to the principal resonance of the apparent mass is also minor in standing subjects.

The apparent mass at the resonance frequency reflects the damping properties inherently present in the mechanical system of interest, so differences in the apparent masses at resonance observed between the three different upper-body postures may be caused by changes in the damping of the human body. Wakeling et al. [15] found that the damping of the muscles of the legs increased with increasing muscle activity. It may be reasonable to assume that similar properties are present in the muscles of other parts of the body. In the present study, in the lordotic posture and the anterior lean posture, increases in muscle activity in the upper body may have caused increases in the damping of the muscles that may have contributed to decreases in the apparent mass at the resonance frequency, compared to that in the upright posture (Fig. 2 and Table 3). There may be a significant contribution of the motion of the viscera to the resonance of the apparent mass, as discussed by Kitazaki and Griffin [13] and Matsumoto and Griffin [14] for seated subjects. It can be hypothesised that the change in the damping discussed above might have changed the dynamic properties of the viscera, resulting in the decrease in the apparent mass at resonance observed in the experiment. Although there is a possibility of increases in stiffness due to increases in muscle activity, the effect of any stiffness change on the resonance frequency was not clear in the experiment. This might imply that at resonance the effect of the change in the damping activity was more dominant than the effect of changes in the stiffness of the muscles. A minor effect of changes in the damping on the resonance frequency of the apparent mass led to no significant difference in the resonance frequencies between the three upper-body postures.

The differences in the apparent masses at resonance between the three upper-body postures were probably not caused by changes in the geometry of the spine if there are only minor contributions from bending motion of the spine to the principal resonance [14].

The difference in the resonance frequency between the "knees bent" posture and the "knees more bent" posture implies softening of the total body response when bending the legs at the knees during exposure to vertical vibration. In the "knees more bent" posture, an increased horizontal distance between the centre of mass of the body and the knee joint might have increased the mass moment of inertia of the body about the knee joint. If the rotational stiffness was not changed, the greater mass moment of inertia would contribute to a reduction in the resonance frequency in the "knees more bent" posture than that in the "knees bent" posture.

4.3. Effect of vibration magnitude on vertical apparent mass

The principal resonance frequency of the apparent mass decreased with increasing vibration magnitude, exhibiting a "nonlinearity" as reported consistently in previous studies. Edwards and Lange [12] reported that the resonance frequency of the mechanical impedance of the standing body decreased from 5 to 4 Hz with increasing vibration magnitude from 0.2 to 0.5 g in a "standing relaxed" posture. Matsumoto and Griffin [1] investigated the effect of vibration magnitude on the dynamic response of the standing body and concluded that the main resonance frequency of the apparent mass decreased from 6.75 to 5.25 Hz when increasing the vibration magnitude from 0.125 to 2.0 $\mathrm{m\,s^{-2}}$ rms in a "normal" posture in which subjects kept their upper body in a comfortable and upright position with legs straight and locked. Decreases in the resonance frequency with increases in vibration magnitude have also been reported in studies with seated subjects (e.g., Refs. [2–8]).

In the present study, the apparent mass at the resonance frequency tended to decrease with increasing vibration magnitude. In previous studies, the effect of vibration magnitude on the apparent mass (or mechanical impedance) at the resonance frequency has not been consistent. Edwards and Lange [12] found a decrease in the mechanical impedance at the resonance frequency with increasing vibration magnitude in a "standing relaxed" posture. For seated subjects, Nawayseh and Griffin [3] reported a similar finding: a trend towards a reduction in the apparent mass at the resonance frequency with increases in vibration magnitude. However, Matsumoto and Griffin [1] have reported no significant influence of vibration magnitude on the apparent mass at the resonance frequency. Mansfield and Griffin [6] found the apparent mass at the resonance frequency tended to increase slightly with increasing vibration magnitude for seated subjects. These different variations in the apparent mass at the resonance frequency may be caused by different vibration conditions (e.g., different excitation magnitudes and frequencies), variability between subjects and different postures in which different vibration modes may contribute to the resonance.

Matsumoto and Griffin [2] concluded that "nonlinear characteristics in the apparent masses of seated subjects were less clear when muscle tension in the abdomen was controlled". In this study with standing subjects, both the lordotic posture and, possibly, the anterior lean posture, involved some control of muscle tension in the abdomen and tended to have reduced nonlinear characteristics in the resonance frequency of the apparent mass and the apparent mass at resonance compared to the upright posture (Table 4).

In the "knees bent" posture and the "knees more bent" posture, small differences in the resonance frequency of the apparent mass (both the absolute values and the values in percentages) and the apparent mass at the main resonance frequency with changing vibration magnitude might be attributed to some modification of voluntary or involuntary muscle activity.

Although there were signs of a reduction in nonlinearity with postures involving increased muscle tension in this study, the increases in muscle tension were not sufficient to eliminate the nonlinearity. This is apparent in the significant differences in the resonance frequencies caused by changes in vibration magnitude for postures in which the tension in some muscles were increased with respect to the upright posture (Table 4). Between the upright posture and all other postures, there were no significant differences in the size of the percentage differences in the resonance frequency caused by changes in vibration magnitude.

4.4. Effect of posture on the cross-axis apparent mass

An appreciable cross-axis apparent mass was found in the present study (Figs. 4–6). This is caused by a two-dimensional motion of standing subjects, as observed previously [1]. In a ''normal standing'' posture, the transmissibility from vertical floor vibration to the fore-and-aft motion at the first thoracic vertebra was greater than that at the eighth thoracic and the fourth lumbar vertebrae at the resonance frequency in the vicinity of 5 Hz [1]. At the resonance frequency of the apparent mass, a significant phase difference in the fore-and-aft transmissibilities was found between the first thoracic vertebra and the fourth lumbar vertebra, while the phase of the fore-and-aft transmissibility to the fourth lumbar vertebra was similar to that of the knee [16]. These may imply a forward rocking motion of the upper body about the pelvis and a fore-and-aft movement of the pelvic region and the lower body, which may be caused by a rotational motion about the ankle, contributing to the fore-and-aft cross-axis apparent mass at the first resonance frequency in the upright standing posture observed in this study.

The fore-and-aft cross-axis apparent mass was affected by bending of the spine, as shown in Fig. 5, although the effect of bending the spine was not clear in the vertical apparent mass. The two fore-and-aft motions at resonance described above may increase or decrease the fore-and-aft force exerted on the floor by the body, depending on the magnitude and phase of the two motions. The magnitude and phase of the two fore-and-aft motions might have been changed by the bending of the body investigated in this study. In the lordotic posture, the lordotic upper body may have increased muscle tension in the pelvic region and reduced the freedom of the pelvis to rotate, which may have resulted in the reduced phase difference between the motion of the upper body and the motion of the lower body in the fore-and-aft direction. This may explain the increased fore-and-aft force on the floor in the lordotic posture compared to that in the upright posture. In the anterior lean posture, the upper body leant forward and increased the horizontal distance between the centre of mass of the upper body and the pelvis and may have increased the rocking motion of the upper body about the pelvis induced by the vertical vibration. The fore-and-aft force caused by the motion of the lower body may have been reduced, or cancelled, by the fore-and-aft force induced by the rocking of the upper body about the pelvis, if these two forces acted out of phase. This mechanism may have resulted in less fore-and-aft cross-axis apparent mass in the anterior lean posture than in the upright posture (Fig. 5).

Matsumoto and Griffin [1] found that the transmissibility to the knee in the fore-and-aft direction in a ''legs bent'' posture (similar to the ''knees bent'' posture in the present study) had a first resonance around 3 Hz at a vibration magnitude of $1.0\,\mathrm{m\,s^{-2}}$ rms. They also reported that, in a ''legs bent'' posture, the transmissibility to the fore-and-aft motion at the first thoracic vertebra was greater than that at the eighth thoracic vertebra and the fourth lumbar vertebra at the resonance frequency [1]. This suggests that a bending motion at the knee, which may be coupled with a rocking motion of the upper body, was involved in the resonance at around 3 Hz. The force in the fore-and-aft direction induced by these motions may have contributed to the appreciable fore-and-aft response at the lower resonance frequency in the ''knees bent'' posture and in the ''knees more bent'' posture observed in this study.

A second resonance of the cross-axis apparent mass was observed around 12 Hz in the upright posture, the lordotic posture, the ''knees bent'' posture and the ''knees more bent'' posture. Mansfield and Griffin [8] found a resonance of the transmissibility to the rotational motion of the pelvis for seated subjects at around 12 Hz, although the rotational motion of the pelvis observed in seated subjects is not necessarily found in standing subjects at the same frequency. A peak in the transmissibility to pitch motion of the pelvis was observed at around 12 Hz by Matsumoto and Griffin [1] with standing subjects in a ''legs bent'' posture. It may be hypothesised that the resonances of the cross-axis apparent mass in different standing postures observed at around 12 Hz in this study were associated with a pitch motion of the pelvis.

4.5. Effect of vibration magnitude on the cross-axis apparent mass

Nonlinear characteristics in the cross-axis apparent masses of the standing subjects were not observed as clearly as in seated subjects reported in previous studies (e.g., Refs. [2–4]). There was no clear effect of posture on the nonlinearity in the cross-axis apparent mass observed in this study (Table 7). A similar finding has been reported for seated subjects [2,3]; increases in muscle tension had no obvious effect on the nonlinearity in the fore-and-aft dynamic responses to vertical vibration. The results of the present study imply that the cause of the nonlinearity in the apparent mass had only a minor effect on the nonlinearity in the cross-axis apparent mass.

4.6. Correlation between the apparent mass and the cross-axis apparent mass

The first resonance frequencies of the cross-axis apparent mass were close to the principal resonance frequencies of the vertical apparent mass. This may suggest a common vibration mode that is responsible for the principal resonance in the vertical apparent mass and the first resonance in the cross-axis apparent mass. In a study of mathematical models of standing subjects, Matsumoto [16] concluded that the vibration modes contributing to the principal resonance of the vertical apparent mass were the vertical motion of the viscera mass moving in phase with the axial deformation of the tissues of the sole, and a pitch motion of the pelvis moving out of phase with a pitch motion of the upper body. It may be assumed that, at the resonance, the pitch motion of the pelvis mentioned above is probably coupled with rotation of the legs about the ankle joints, causing fore-and-aft motion at the pelvis as mentioned in the preceding section. The rotational motions of body segments involved in the vibration mode associated with the principal resonance of the vertical apparent mass would induce fore-and-aft forces at the floor that would be seen as a resonance in the cross-axis apparent mass at the same frequency, as observed in the experiment.

In the “knees bent” posture and in the “knees more bent” posture, although there were significant correlations between the first resonance frequency of the cross-axis apparent mass and the principal resonance frequency of the apparent mass (Table 8), there were significant differences between those resonance frequencies (Table 9). This does not support the hypothesis that similar vibration modes are involved in both the principal resonance of the apparent mass and the first resonance of the cross-axis apparent mass. However, for the “knees bent” posture and the “knees more bent” posture, a low coherency at low frequencies in the fore-and-aft direction may suggest the need for further investigations to support or reject the hypothesis. The significant correlation found between the resonance frequencies may imply that those frequencies are in some way related to each other.

5. Conclusions

Standing subjects exposed to vertical vibration show a two-dimensional dynamic response in the mid-sagittal plane with appreciable forces in both the vertical and fore-and-aft directions at the floor. At resonance, the cross-axis apparent masses in the fore-and-aft direction were about 30% of the static masses of subjects. The first resonance of the cross-axis apparent mass was at a frequency close to the principal resonance frequency of the vertical apparent mass. This implies a common vibration mode that may be responsible for the principal resonance of the apparent mass and the cross-axis apparent mass.

There were only minor effects of variations in posture of the upper body on the apparent mass resonance frequencies. However, the apparent mass resonance frequency reduced significantly with bending of the legs at the knees, as reported previously. In some postures, there was no clear resonance in the cross-axis apparent mass: the fore-and-aft forces may have been cancelled by phase differences between the forces induced by movements of several parts of the body.

Nonlinear characteristics were observed in the vertical apparent mass and, less clearly, in the fore-and-aft cross-axis apparent mass. In some postures in which subjects increased muscle tension, the nonlinearities tended to be less clear than when standing in a normal upright posture.

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